Energy, Exergy, and Economic (3-E) Analysis of Thermal Power Plant Systems:- A State of Art Literature Review

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Abstract:

Lifeblood of today's modern civilization is availability of economical energy in abundance. Now a days world is suffering from the energy crisis. This is due to excessive dependence on traditional energy resources. In order to mitigate energy crisis, there is a need of taking some critical steps for energy conservation as energy and money are directly proportional. Exergy is a measure of available energy. Exergy analysis is considered to be one of the best methods that have been used to conquer energy crisis. It is a technique of thermodynamic analysis based on the second law of thermodynamics which carries out detailed analysis of different types of equipments and processes of a complex system. Using this concept one can find out how much more improvement is possible in any device or system. This paper reviews fundamental research on energy, exergy and economical (3E) analysis of thermal systems. The future scope of possible research in this field is also briefly discussed.

Keywords: Economical, energy analysis, exergy analysis, powerplant, Second law of thermodynamics.

1.INTRODUCTION

England gave birth to an industrial revolution in the eighteenth century. The researchers purposed four critical components for the industrial revolutions which are Technology, Capital, Labor, and Energy. So, energy consumption plays a crucial role in the economical growth of any nation. Energy resources are very limited and that is why the consumption of energy is one of the biggest problems in today's scenario. This has developed an interest amongst scientists and researchers to pay greater attention to the energy consumption field. This leads to the development of new devices and techniques for the optimum utilization of energy resources. Nowadays, thermal power plants are playing a significant role in energy production and therefore attention has to be paid to the optimization of thermal power plants.

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Due to energy crisis and costlier prices of energy, there is a need for the development of different energy sources. Thermodynamics also plays very important role in this field, and it includes the analysis of different processes and plant system.

In thermodynamics, energy is classified into two categories: high-grade energy (work) and low-grade energy (heat). It is well known that the complete conversion of low-grade energy (heat) into high-grade energy, i.e., work is impracticable. So, the portion of low-grade energy which is procurable for conversion is known as "EXERGY". The term 'Exergy' is the combination of two Greek words i.e. ex (which means out) and Ergon (which means work). Thus, exergy is the useful work which we can obtain from the input heat (low-grade energy).

1.1 Why Study Exergy:-

During the last few decades, analysis of exergy has begun to be used for the optimization of various systems because of the following reasons:-

- Exergy is the measure of available energy or one can say that it is the portion of energy which can be transformed into work. Exergy is the detailed analysis of different types of equipment and processes in a complex system. Thus, by this concept, we can find out how much more improvement is possible in any device or system.
- By exergy analysis, we can compare the different components of various systems and come to know about devices or equipment that needs upgradation in order to improve the efficiency of the system.
- Exergy analysis also plays an important role in design making decisions.
- For the efficient use of energy in industrial ecology, we need exergy analysis.
- Exergy analysis is also used to determine the magnitude, type, and location of various energy losses in the system.

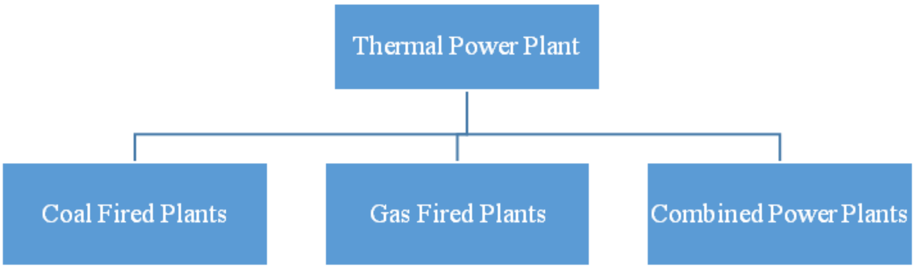
Thus, we can say that the exergy analysis has its own importance in improving the performance of various systems.

Recently, a large number of studies have been carried out by different researches in different parts of the world on the exergy analysis in various system applications. The aim of this paper is to review the work done by different researchers in the field of exergy analysis. Therefore and to make suggestions further work that needs to be done in this field.

2. LITERATURE REVIEW

For the current study, the thermal power plant has been categorized into three different power plant stations, as shown in Figure 1. The classification of the thermal power plant maybe done on the basis of the heat source.

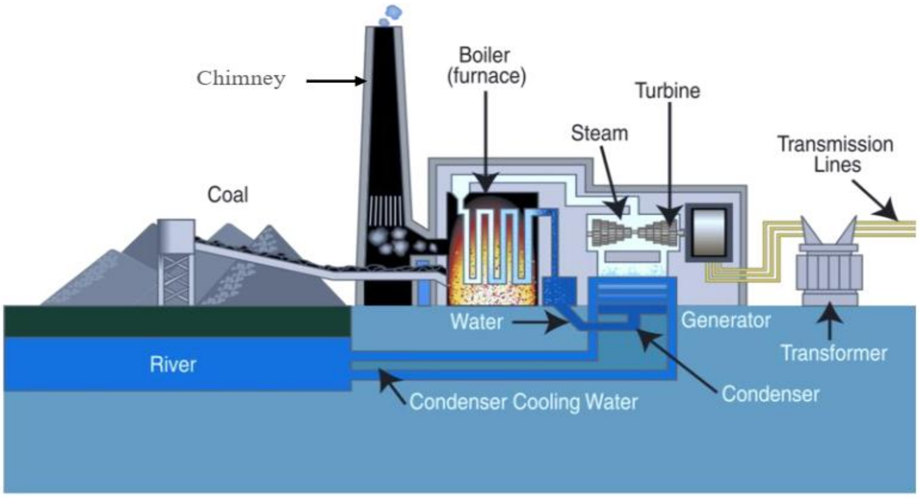
Figure 1 **Classification of thermal power plant**



2.1 Exergy Analysis of Coal-Fired Power Plant

Coal-fired power plants are one of the power plants which uses combustion of coal as a heat source to produce electricity. Most developing countries like South Africa, India, etc., use coal as the primary source of electricity generation. The working principle and the generation of electricity from coal is shown in Figure 2.

Figure 2 **The working principle of Coal-fired power plant**



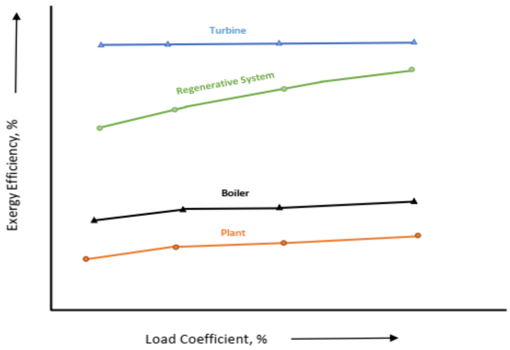
A Number of researchers and scientists focused their research work towards an exergy analysis in coal-based power plants, out of those few are described below:

Sengupta S. et al (2007) conducted an experiment for the exergy examination of the 210 MW coal operated thermal power plant. For their analysis, they divided the whole plant into three divisions, where the first division was only for a turbogenerator with its inlet and outlet. The Second division was meant for turbo generators with feed pump, regenerative heaters, and condensers and for the third division, they considered the entire cycle with plant auxiliaries. By this way, they were able to calculate the contribution of various components for exergy destruction in a thermal power plant. It was observed that the boilers were producing the maximum irreversibility in the power plant, which caused around 60% exergy destruction in the plant. The exergy efficiency was calculated by the following equation:

$$\eta_e = \frac{P_o}{E_i - E_f} \qquad (1)$$

where, P_o is the net power output, and E_i and E_f represent the exergy flow rate across the different control system. Li Y. and Liu L. (2012) carried out an experiment for finding the exergy destruction in the coal-based power plant. For this work, they considered the 300 MW coal-based power plant under different loading conditions. They found that the boilers are the major source of the exergy destruction as compared to the other components of the entire plant. This was determined by considering the different boiler thermodynamic processes like combustion, heat exchanging and dissipation. Figure 3 shows the performance of the plant under various loading conditions.

Figure 3 Exergy efficiency of the turbine, regenerative system, boiler and overall plant under different loading conditions.



Kumar K. et al (2013) carried out an experiment to analyze the exergy analysis of the operating condition of boilers. They used mass and exergy balance to find out the exergy analysis of the operating condition of the boiler. They concluded that with the use of bituminous coal, one can achieve maximum exergetic efficiency of boilers. It has been also observed that the maximum exergy destruction takes place due to the combustion process. Rudra S. et al (2008) carried out a research to study the coal-based thermal power plant using different steam conditions like sub-critical, supercritical and ultra-supercritical condition. A computer-based process simulation was used for the exergy analysis and they considered the 500 MW power plant for this study. According to them the maximum possible plant efficiency for the supercritical and ultra-supercritical thermal plant is 40.2% and 44.8% respectively. Kulkarni H.R. et al (2017) carried out studies to determine the energy analysis for 32 MW coal-based thermal power plant. The main objective of this work was to identify the magnitude as well as the location of exergy loss during the process by various components of the plant. The exergy and energy balance equations were used to find out the various losses. They concluded that the maximum losses are occurring at boiler followed by turbine and heat exchanger respectively. The overall efficiency of the plant was 30 %, and the losses at the boiler and turbine were 42% and 38% respectively. The research work done by other researchers with their major findings are summarized in Table 1.

Table 1 Summary of exergy analysis of coal-fired plant done by different researchers

Author	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
Adibhatla S. et al (2014)	660	Y	Y	N	It has been found that the Boiler has a maximum rate of exergy destruction but there is no energy loss during the combustion process.
Mitrovica D. et al (2010)	348.5	Y	Y	N	The irreversibility rate is maximum in the boiler as compared to other components while the loss of energy occurs, mainly in the condenser.
Xiong J.et al (2011)	800	N	Y	N	The exergy efficiency of the conventional system is higher than that of Oxy combustion system.
Ganapathy T. et al (2009)	50	Y	Y	N	The maximum exergy losses occur in the combustor, whereas maximum energy losses occur into the condenser.
Verkhivker G.P. et al (2001)	232.6	N	Y	Y	The reduction in exergy destruction can be achieved by reducing the temperature difference of the heaters.
Bolatturk A. et al (2015)	150	Y	Y	Y	The Condenser has minor exergy losses, while major

					exergy losses occur in the boiler as compared to the other components.
Rashad A. et al (2009)	315	Y	Y	N	Maximum exergy destruction occurred in the turbine, whereas major energy losses take place in the condenser.
Ahmadi G.R. et al (2016)	200	Y	Y	N	The Boiler was found to be the most wasting exergy equipment while from the energy point of view, the condenser was the major energy-wasting equipment.

2.1.1 Observations

Like many other countries of the world, India also depends largely on coal for electricity and power generation. Approximately 60 % of the total power generation in India is done with coal-fired thermal power plants. In 2011, India was also the third largest coal producing country in the world. Thus coal is an essential component of the current Indian economy. But, the overall efficiency of the coal-based power plants ranges from 30% to 40%. From the literature review, it can be concluded that the boilers and the condenser are the two major components where maximum exergy destruction occurs. Therefore one needs to pay more attention to these components for the efficient running and to enhance the efficiency of coal plants. Now-a-days, researchers and scientists are trying to improve the overall efficiency of coal-based plants beyond this range by introducing the supercritical pressure concepts. However most of these efforts are proving impractical from economic viewpoint.

2.2 Exergy Analysis of Gas-Fired Power Plant

Gas turbines or gas-fired power plants are primarily used for large-scale power generation. These consists of mainly three components: compressor, combustor or combustion chamber and the turbine. The main advantage of the gas-fired power plant is their fuel flexibility. The underlying principle of the gas turbine power plant is shown in Figure 4.

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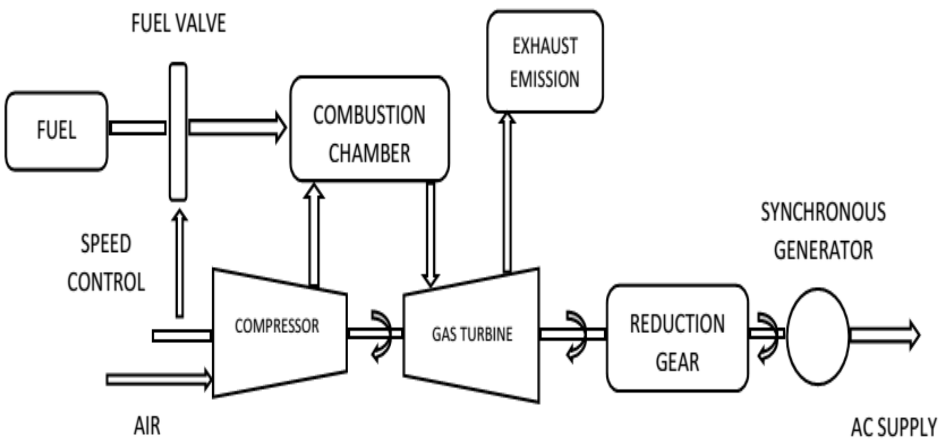
Figure 4 Simple gas turbine principle



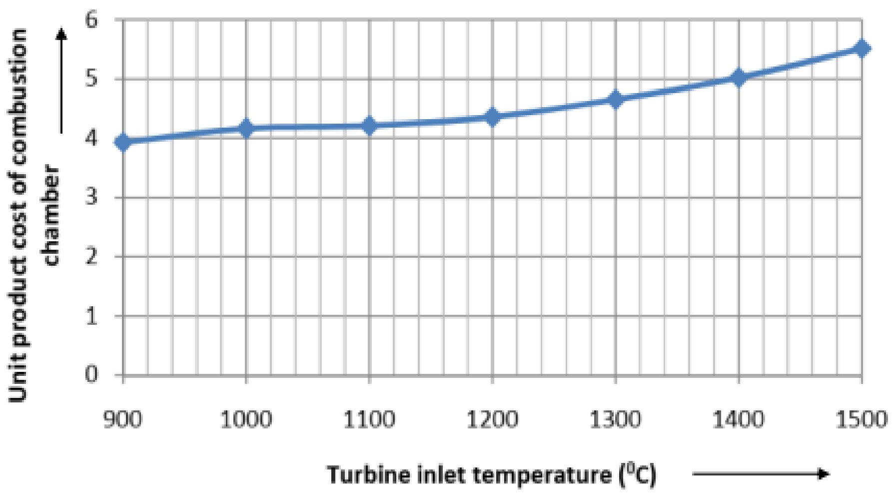
Researchers have worked in this field not only to optimize different parameters of gas-fired power plants, but also to investigate the different sources of exergy destruction by considering the 3-E analysis system, i.e. Energy, Exergy, and Economics analysis. The research work carried out by few researchers is briefly discussed below:

Martin A. et al (2016) carried out research to evaluate the performance of 20MW gas turbine power plant using exergy analysis. For this study, they used mass and energy conservation law with the first and second law of thermodynamics. They found that the maximum and minimum exergy destruction occurred in the combustion chamber and compressor respectively, due to the un-combusted fuel, heat loss during the combustion process and uncompleted combustion. 71.03% exergy destruction occurred in the combustion chamber, whereas; in the compressor, only 12.33 % exergy destruction occurred. They also found the overall efficiency and exergy efficiency using the first law of thermodynamics and their magnitude was 33.77% and 32.25% respectively. The overall efficiency was calculated by the following equation

$$\eta_o = \frac{W_{net}}{E_x} \qquad (2)$$

where W_{net} and E_x are the net work done by the gas turbine, exergy rate respectively. Pattanayak L. (2015) calculated the exergy destruction for each component of the gas turbine using a modeling approach. This analysis was done for 88.71 MW gas turbine under different loading conditions. It was observed that the maximum exergy destruction occurred in the combustion chamber (CC). He also found that the overall efficiency of the cycle and its individual component efficiency decreases with a decrease in gas turbine load conditions. Gupta M. and Kumar R. (2015) carried out research to evaluate the performance of open cycle gas turbine plant using the exergoeconomics concept. 25 MW gas turbine power plant was considered for this study. The main purpose of this study was not only to optimization of parameters but also to evaluate the effect of the inlet turbine temperature on unit product price of the combustion chamber. It was observed that the unit product price of combustion chamber rises with a rise in inlet turbine temperature as shown in Figure 5. They also conclude that the inlet turbine temperature and compressor pressure ratio have a major impact on the open cycle gas turbine plant performance.

Figure 5 Effect of inlet turbine temperature on the unit price of the combustion chamber



Rashad A. and Maihy A. El (2009) calculated the energy and exergy losses under different load conditions for Shobra El-Khima power plant, Egypt. Component wise modeling method was used to evaluate the performance of the plant. The Result shows that the percentage proportion of exergy loss to the total exergy loss was calculated to be the highest in the turbine division follow up by the condenser at maximum and 75 % load estate, but at 50 % load estate, feed water heaters represented the more exergy destruction than the condenser. They also determined the thermal and exergy efficiency of the plant according to the specific heat input to the steam, and it was found around 43% and 44%-48% respectively. The research work carried out by other researchers are summarized in Table 2.

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Table 2 Summary of exergy analysis of gas-fired power plant done by different researchers

Author	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
Khaldi F. et al (2011)	150	N	Y	N	The major source of exergy destruction in gas turbine was found to be the chemical reaction in the combustion chamber at full load.
Song T.W. et al (2002)	146.2	Y	Y	N	Combustor was found to be the major source of exergy destructor & they also found out the combustor was the most inefficient apparatus as compared to other apparatus in gas-fired power plant.
Anozie A. N. et al (2013)	_	N	Y	Y	The performance of the thermal plant not only depend upon the reference temperature and boiler efficiency but also on the condenser efficiency.
Alawa B.T. L. et al (2013)	20	Y	Y	N	The boiler found to be the major source of available energy destruction in gas-fired power plant.
Kumari A (2015)	_	Y	Y	N	The rational efficiency of the basic gas turbine cycle is found to be the lesser than the inter-cooled gas turbine cycle.
Fouladi et. Al (2010)	_	N	Y	Y	The Combustion chamber as compared to other components of gas plant found to be the major source of exergy destructor.
Fagbenle R.L. et al (2007)	53	Y	Y	N	Exergy loss in the combustor found to be the highest as compared to the other components of the plant.

2.2.1 Observations

Gas fired power stations are those which transform the heat energy into electricity by the combustion of natural gas as fuel. A gas power station provides more operational flexibility as well as clean burning compared to coal

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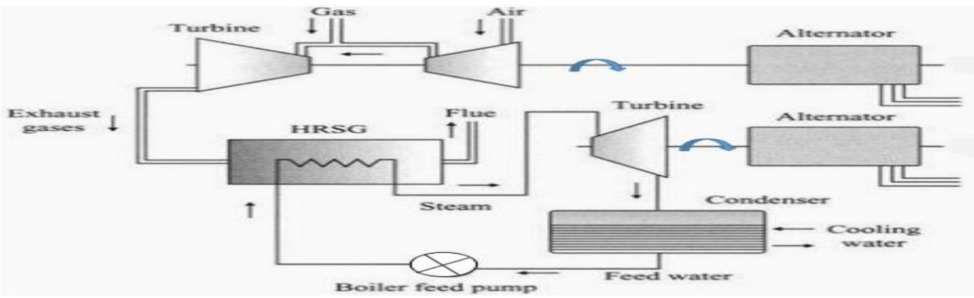
power plant. The other advantages of the gas fire station over coal stations are quick starting time, lower emission and higher efficiency. However a lot of work needs to be done to improve their efficiency and optimize the various parameters. From literature review, it has been observed that the maximum exergy destruction occurs in the combustor chamber followed by the turbine. This study also shows that the condenser efficiency also plays a vital role in order to calculate the plant performance. These aspects need to be kept in view while efforts are made to design more efficient gas fired power plants.

2.3 Exergy Analysis of Combined Power Cycle

In the Combined cycle control power plant, a gas turbine generator is utilized to produce the power. However, waste heat is used to make extra power by utilizing a steam turbine. Thus the combined cycle power plants have higher efficiency compared to the conventional power plants. The gas turbine used in the combined power cycle plants converts the gas fuel energy into mechanical energy or electricity, whereas the steam turbine is used to produce additional electricity from the waste heat. The working of a combined cycle power plant is shown in Figure 6.

Figure 6 Working principle of combined cycle power plant



Some exploratory work done by different researchers in this field is briefly as under:-

Rezaee V. and Houshmand A. (2015) carried out an experiment to analysis the exergy as well as the energy of a combined power generation system which consists KCS11 (kalian cycle system 11) and PEMFC (proton exchange membrane fuel cell). This system is capable of converting the low-temperature waste heat into the electric power generation. The main purpose of this research was to determine the possible improvement of this hybrid system. It was found that without the KCS11, the exergy and energy efficiency improved, about 1.5% and 1.75% respectively. Garg P.D. et al (2013) conducted an experiment to evaluate the performance of combined cogeneration power cycle on the basis of exergy and energy approach. Exergy destruction, combined cycle cogeneration efficiency, combined cycle efficiency, and power output were investigated under different operating conditions. Their results show that the major exergy losses developed in the combustion chamber (about 35 % of total exergy losses) as compared to the exergy losses in other components of plants. Ameri M. et al (2007) carried out studies to determine the irreversibility of each component of the Neka combined power cycle plant using exergy analysis. Their result shows that the major source of exergy loss in plant occurred in

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the combustion chamber due to its irreversibility, followed by the heat recovery steam generator (HRSG). They also calculated the exergy and thermal efficiency of the plant, and it is found to be 45.5% and 47 %, respectively, without the use of duct burner and with the use of duct burner the exergy and thermal efficiency decreased from 45.5 % to 44 % and from 47 % to 46 % respectively. Moneim S. A. A. and Hossin K. M. (2013) carried out a research to do the exergy and energy analysis of combined cycle equipped with a supercharged boiler. The main purpose of this study was to determine the effect of the compressor pressure ratio, the excess air factor and the inlet temperature of the gas turbine on the working performance of the supercharged boiler combined cycle. Their result shows that at the same value of operating parameters, the supercharged boiler combined cycle (SBCC) gives high output power (nearly 2.1 times) as compared to the conventional combined cycle, but the efficiency of the conventional combined cycle was found to be higher than that of the supercharged boiler combined cycle. Table 3 summarizes important work done by other researchers in the field of the combined power plants.

Table 3 Combined cycle power plant 3E-analysis

Author	**Capacity (MW)**	**Energy analysis**	**Exergy analysis**	**Economic analysis**	**Findings**
Reddy B.V. et al (2007)	_	N	Y	N	The effect of various parameters on the exergetic efficiency of the gas-fired combined cycle power generation has been calculated on the basis of exergy analysis.
Boyaghchi F. A. et al (2015)	420	N	Y	N	The sensitivity of each component of exergy destruction in combined power cycle plant has been calculated.
Ganjehkaviri A. et al (2014)	_	N	Y	Y	The exergoeconomics analysis and thermodynamics modeling has been done in combined power plant cycle.
Baghernejad A. and Yaghoubi	_	Y	Y	N	With the help of design plant data, a comprehensive exergy and energy analysis of integrated solar combined power cycle has

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M. (2010)					been carried out.
Alessandro F. and Russo A. (2002)	_	N	Y	Y	To improve the overall efficiency of the combined cycle power plant and also to optimize the operating parameters of the heat recovery steam generator, a method has been proposed.
Athari H.et al (2014)	_	Y	Y	Y	The 3E analysis i.e. Energy, Exergy, and exergoeconomics have been applied to the biomass integrated post-firing combined power plant.
Petrakopoulou F. et al (2012)	_	N	Y	N	Using conventional and advanced exergetic analysis in combined power cycle plant, the maximum exergy destruction has been found by the combustion chamber.
Ameri M. et al (2008)	420	N	Y	N	In combined power plant cycle, it has been pointed out that the combustion chamber has a much lower efficiency as compared to the other gas turbine efficiency.

2.3.1 Observations

A combined cycle power plant uses both steam and the gas turbine to generate the electricity and thus the overall efficiency of combined power cycle is higher than the conventional power cycle plant. Literature review shows that the combustor chamber is the least efficient component in the combined power cycle due to its irreversible nature. This study also shows that the supercharged boiler can provide more power output in the same operating conditions as compared to a conventional type boiler. The efficiency of such plants can be further improved by blade cooling and supplementary firing in the gas turbine and at the Heat recovery steam generator (HRSG).

3 Concluding observations

Recently, a large number of studies have been carried out by different researches throughout the world on the exergy analysis in various system applications. This review paper aimed at highlighting the 3-E analysis of thermal power plants done by different researchers in the field of thermal power plant engineering. For better appreciation thermal plants have been categorised into three categories, i.e., coal-based plant, gas-based plant, and combined power cycle plant. Research papers, including exergy as well as energy and economic analysis have been taken into consideration in this review.

The energy crisis which the world is facing now-a-days has motivated researchers to work to enhance the efficiency of existing power plants and also to find out the alternative ways of electricity generation that least affect the environmental conditions. The exergy-based technique is one of the powerful tools to analyse the performance of the existent power plants. The results drawn out from this study maybe summarized as under:-

a. Current research shows that using the concept of exergy analysis one can find out how much more improvement is possible in any device or system. Thus, exergy plays a significant role in the field of optimisation of thermal plants.
b. As compared to the conventional approach which is based on the first law of thermodynamics, the exergy-based analysis gives better insight into the working performance of a power plant.
c. Coal power plant works in the efficiency range of 30 – 40 %. Many researchers have tried to enhance the efficiency of coal-based power plants by introducing different concepts like super-critical pressure concept. However from the economic aspect all these efforts seems to be impractical.
d. This study also shows that in the coal-based power plants the boiler and the turbine are the main components where major exergy losses take place.
e. In gas-fired and combined power plants combustor chamber is found to be the least efficient component as compared to the other. Maximum exergy losses occur in the combustion chamber due to its irreversible nature, so one need to critically analyse the combustion chamber to enhance the performance of these power plants.
f. Inlet temperature and the compressor pressure ratio have a major role in the open cycled power plant performance.
g. Condenser efficiency also plays a vital role to calculate the performance of the gas-fired power plants.
h. Combined power plants have higher efficiency than the conventional type of power plants which can be further improved by introducing the supercharged boiler, turbine blade cooling and heat recovery steam generators in the power plants.

5. Research gap & Scope of further work

In this paper, the thermodynamic analysis of power plants has been done from exergy, energy and economic (3-E) viewpoint. The objective of this study was to highlight the previous work done by different researchers in the field of thermal power plants and also to highlight the shortcomings. The research gaps observed from the above literature review are briefly summarized below. Some of the possible directions in which further work needs to be undertaken are also mentioned.

a. Major work has been done on the thermo-dynamical aspect of thermal power plants, but not much work has been done from the economical point of view primarily, acknowledging the second law of thermodynamics.
b. Exergy analysis can only tell us where and how we can improve our system, but it does not tell us about whether it is possible to achieve those goals practically or not. This problem can only be resolved by combining economical aspect with the exergy analysis.
c. Very less amount of work has been done to analyse the power plants at different operating load conditions.
d. From the exergoeconomic point of view, not much work has been done to maximize the plant performance.
e. Time basis analysis also needs to be considered to determine the performance of the power plants.

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Nomenclature

P_o	Net power output (W)
E_i	Initial exergy flow rate (W)
E_f	Final exergy flow rate (W)
E_x	Exergy rate of the system (W)
W_{net}	Net work done by the gas turbine (J)
Greek symbols	
$\square_e$	Exergy efficiency defined by equation (1)
$\square_o$	Overall efficiency of plant defined by equation (2)
HRSG	Heat recovery steam generator
KCS11	Kalian cycle system 11
MW	Mega Watt
PEMFC	Proton exchange membrane fuel cell
SBCC	Supercharged boiler combined cycle
SEKPP	Shobra El-Khima power plant
3-E analysis	Energy, Exergy& Economics analysis